NBSIR 88-3761

Predicting Formaldehyde Concentrations in Manufactured Housing Resulting From Medium-Density Fiberboard

Samuel Silberstein

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
Building Environment Division
Gaithersburg, MD 20899

April 1988

Prepared for:

U.S. Department of Housing and Urban Development
Washington, DC

NBSIR 88-3761

PREDICTING FORMALDEHYDE CONCENTRATIONS IN MANUFACTURED HOUSING RESULTING FROM MEDIUM-DENSITY FIBERBOARD

Samuel Silberstein

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
Building Environment Division
Gaithersburg, MD 20899

April 1988

Prepared for:
U.S. Department of Housing and Urban Development
Washington, DC

U.S. DEPARTMENT OF COMMERCE, C. William Verity, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

PREDICTING FORMALDEHYDE CONCENTRATIONS IN MANUFACTURED HOUSING RESULTING FROM MEDIUM-DENSITY FIBERBOARD

1. Introduction

In 1984, HUD issued Manufactured Home Construction and Safety Standards limiting formaldehyde emissions of particleboard and plywood paneling that was manufactured using urea-formaldehyde resins for use in manufactured homes [1]. The standards specified that the formaldehyde concentration of particleboard present in a measuring chamber at a loading (that is, the exposed pressed-wood product surface area per unit volume of the space) of 0.13 ft^2/ft^3 (0.4265 m^2/m^3) be limited to 300 ppb, and that the concentration of plywood present in a measuring chamber at a loading of 0.29 ft^2/ft^3 (0.9514 m^2/m^3) be limited to 200 ppb. The chamber, which is specified in the standard, must be operated at 25°C and 50% RH, with an air exchange rate of 0.5 h^{-1}. Because concentration is invariant with volume or pressed-wood product surface area as long as loading is maintained constant, the same loadings of these products would result in the same formaldehyde concentrations in manufactured homes, provided that temperature, relative humidity and air exchange rate are kept constant.

The other major pressed-wood product manufactured from urea-formaldehyde resins, but not covered by the standards, is medium-density fiberboard (mdf). The purpose of this study is to predict the formaldehyde concentration of a chamber containing only medium-density fiberboard, so that if particleboard and plywood meeting the emissions limits of the HUD standards were added to the chamber at the maximum loadings permitted by the standards, the formaldehyde concentration would remain below 400 ppb.

Formaldehyde concentrations predicted for each type of pressed-wood product may not simply be added together to predict the concentration resulting from a combination of products. For example, if both particleboard and plywood were present at the loadings and concentrations permitted by the HUD standards, then the resulting concentration at 25°C, 50% RH, and an air exchange rate of 0.5 h^{-1} would be 330 ppb, which is far lower than the sum of 300 ppb and 200 ppb. In fact, the plywood could be said to make a nearly negligible contribution to the concentration. This is because the formaldehyde emission rate decreases with increasing formaldehyde concentration. The emission rate of plywood at 300 ppb formaldehyde is far lower than at 200 ppb, so it contributes much less than an additional 200 ppb formaldehyde to an atmosphere already containing 300 ppb.

In order to study the effects of combinations of pressed-wood products, the concentrations of individual products must first be expressed in terms of formaldehyde surface emission rates. According to Fick's diffusion law, the surface emission rate is linear in concentration with negative slope. Oak Ridge National Laboratory (ORNL) [2] developed models that extrapolate the linear regression coefficients for the Fick's Law expression at standard conditions of 23°C, 50% RH, and 100 ppb concentration, to any other combination of temperature, relative humidity

and concentration. A simple mass-balance indoor air quality model developed at the National Bureau of Standards (NBS) [3] can then be used to obtain concentrations resulting from combinations of products having different emission rates.

Validation studies of the ORNL and mass-balance indoor air quality models were performed at NBS [3]. These studies showed that the models performed well for particleboard and mdf. They did not perform well for plywood; however, the model's predictions for plywood emission rates were higher than those actually obtained so that they still provide an upper bound.

The ORNL and indoor air quality models will be used to give mdf concentrations that satisfy the requirements specified above. These concentrations will be translated into permissible surface emission rates, which will depend on mdf loading. (A small loading will give the same concentration with a higher surface emission rate than a larger loading.) Next, a sensitivity study will be performed. The effects of small variations in temperature, relative humidity, and air exchange rate on formaldehyde concentrations and surface emission rates due to mdf, will be analyzed.

2. Methods

Assume in all that follows that the external formaldehyde concentration = 0 ppb. The external concentration is that outside the chambers and outside the home. Further, let subscripts 1, 2, and 3 refer to particleboard underlayment, hardwood-plywood paneling, and mdf, respectively.

From Fick's diffusion law:

$$ser_i/ser_{i,23,50,100} = a_i - b_i \cdot C \qquad (1)$$

where

C = formaldehyde concentration, ppb.
ser_i = formaldehyde surface emission rate, $mg/m^2 \cdot h$.
$ser_{i,23,50,100}$ = ser_i at 23°C, 50% RH and C = 100 ppb.

ORNL empirically determined the coefficients a_i and b_i to be as follows:

$$b_i = [1 + B \cdot (T - 296.15)] \cdot [1 + E \cdot (RH - 50)]/(C_{bstd} - 100) \qquad (2)$$
$$a_i = b_i \cdot \exp[-c \cdot (T^{-1} - 296.15^{-1})] \cdot (RH/50)^A \cdot C_{bstd} \qquad (3)$$

where

A, B, c, E, and C_{bstd} are given in table 1 for each type of pressed wood product.
T = absolute temperature, K.
RH = relative humidity, %.

According to the NBS indoor air quality model:

$$\Sigma\, l_i \cdot ser_i = C \cdot g \cdot AI \qquad (4)$$

where

C = formaldehyde concentration at equilibrium, ppb.
l_i = loading = $area_i/V$, m^2/m^3.
$area_i$ = exposed surface area of boards of class i, m^2.
V = volume of space, m^3.
g = formaldehyde concentration conversion factor from ppb to mg/m^3 = 1.228×10^{-3} $mg/m^3 \cdot ppb$.
AI = air exchange rate, h^{-1}.

[Unspecified summations should be taken from i=1 to i=3.]

Equation 4 gives the relationship between ser_3 and l_3:

$$l_3 \cdot ser_3 = C \cdot g \cdot AI - l_1 \cdot ser_1 - l_2 \cdot ser_2 \qquad (5)$$

ser_1 and ser_2 can be calculated from equations 2 and 3. For any value of l_3, $ser_{3,23,50,100}$ may be calculated from ser_3, as determined by equation 5, and from a_3 and b_3, as determined by equations 2 and 3:

$$ser_{3,23,50,100} = ser_3/(a_3 - b_3 \cdot C) \qquad (6)$$

In the present report, C is always taken to be 400 ppb in the home.

The mdf measuring chamber concentration can be calculated for any combination of mdf loading and ser_3:

$$l_3 \cdot ser_3 = C \cdot g \cdot AI \qquad (7)$$

According to equation 1:

$$l_3 \cdot ser_{3,23,50,100} \cdot a_3 - l_3 \cdot ser_{3,23,50,100} \cdot b_3 = C \cdot g \cdot AI \qquad (8)$$

$$C = (l_3 \cdot ser_{3,23,50,100} \cdot a_3)/(l_3 \cdot ser_{3,23,50,100} \cdot b_3 + g \cdot AI) \qquad (9)$$

3. Results

3.1. Mdf concentrations and emission rates

Suppose that the temperature, relative humidity, and air exchange rate of a manufactured home are 25°C, 50%, and 0.5 h^{-1}, respectively. Suppose that particleboard and plywood are present at the maximum loadings permitted by the HUD standards. Their formaldehyde emission rates are such that when the two types of pressed-wood products are tested separately in chambers, their concentrations are as large as permitted, i. e. 300 ppb and 200 ppb, respectively. Then the two pressed-wood

products in combination would give a concentration of 330 ppb. How much mdf could be added to the building in order to just reach 400 ppb? The answer is that any combination of mdf that results in a chamber-test concentration of 300 ppb would result in a total home concentration of 400 ppb, provided that the loading, air exchange rate, temperature and relative humidity are the same as for the chamber. This still does not answer the question of how much mdf can be added to the building. This depends on the loading and on the surface emission rate, which can be conveniently expressed as $ser_{23,50,100}$. The higher the loading one wishes to permit, the smaller must be $ser_{23,50,100}$.

The results discussed in the previous paragraph are shown in figure 1 and table 2. The curves are iso-concentration curves; each point on each curve yields an mdf chamber-test concentration as indicated. The combinations of loadings and $ser_{23,50,100}$'s for the curve marked "300 ppb" would result in a total concentration of 400 ppb in the presence of particleboard and plywood. The curve marked "400 ppb" shows the permitted combinations of loadings and $ser_{23,50,100}$'s in the absence of formaldehyde emitters other than mdf. Both the house and chamber-test concentrations would be 400 ppb in this case. The curve marked "200 ppb" shows permitted combinations of loadings and $ser_{23,50,100}$'s if one wishes to incorporate a margin of error, as discussed below in the section on sensitivity. The chamber-test concentration would be 200 ppb in this case, and the house concentration would remain at 400 ppb even if the temperature were slightly higher than 25°C, the relative humidity slightly higher than 50%, and the air exchange rate slightly higher than 0.5 h^{-1}.

4. Sensitivity

One might want to ensure that the formaldehyde concentration of a home remains below 400 ppb for temperatures greater than 25°C, relative humidities greater than 50%, and air exchange rates smaller than 0.5 h^{-1}. In that case, one would choose combinations of mdf loadings and $ser_{23,50,100}$'s that yield lower formaldehyde concentrations in chamber tests than required to meet the 400 ppb limit. For example, figure 2 shows that to ensure that the concentration remains below 400 ppb at a loading of 0.1 m^2/m^3 at 26°C, one would require that $ser_{23,50,100}$ be kept below 1 $mg/m^2 \cdot h$. For 25°C, $ser_{23,50,100}$ would only have to be kept below 2 $mg/m^2 \cdot h$. At 27°C, 50% RH, and an air exchange rate of 0.5 h^{-1}, it is impossible to keep the concentration below 400 ppb because the permitted loadings of other pressed- wood products already result in a greater concentration before addition of any mdf.

Table 3 and figure 3 show the sensitivity of chamber-test concentrations to temperature. The curve shows that the mdf chamber-test concentration changes by about 35 ppb for a change of 1°C to either direction from 25°C. This means that if excursions of 1°C in the chamber temperature commonly occur or cannot be distinguished by the measurement system, one should limit the chamber concentration to about 260 ppb rather than 300 ppb.

Table 4 and figure 4 show the sensitivity of chamber-test concentrations to relative humidity. The curve shows that the mdf chamber-test concentration changes by about 50 ppb for a change of 5% to either direction from 50% RH. This means that if excursions of 5% in chamber relative humidity commonly occur or cannot be distinguished by the measurement system, one should limit the chamber concentration to about 250 ppb rather than 300 ppb.

Table 5 and figure 5 show the sensitivity of chamber-test concentrations to air exchange rate. The curve shows that the mdf chamber-test concentration changes by about 30 ppb for a change of 0.1 h^{-1} to either direction from 0.5 h^{-1}. This means that if excursions of 0.1 h^{-1} in the chamber air exchange rate commonly occur or cannot be distinguished by the measurement system, one should limit the chamber concentration to about 270 ppb rather than 300 ppb.

These results show that excursions of about 50 ppb can be expected from divergences of the temperature, relative humidity and air exchange rate from their specified values. Table 6 shows the effect of two combinations of such divergences. For example, suppose that instead of being at the specified conditions, the chamber is at the first combination of conditions in table 6. If the chamber concentration were limited to 150 ppb at those conditions, then that would be equivalent to a concentration of 300 ppb if at specified conditions (last line of table 6). If one obtained a concentration of 300 ppb instead of 150 ppb, then the equivalent concentration at the specified conditions would be well over 100 ppb higher than 300 ppb at the specified conditions. The divergence at the second combination of conditions would not be as great. Neither of these combinations of conditions would be difficult to obtain during a chamber test. Thus, in order to ensure that mdf emissions truly result in a concentration of 300 ppb at specified conditions, one might want to allow for a margin of error and permit a concentration on the order of 200 ppb. Figure 1 shows the relationship between mdf loading and $ser_{23,50,100}$ in order to obtain a chamber-test concentration of 200 ppb.

5. References

[1] Department of Housing and Urban Development, "Manufactured home construction and safety standards," Fed. Reg. 49, 31996-32008, 1984.

[2] T. G. Matthews, T. J. Reed, B. J. Tromberg, K. W. Fung, C. V. Thompson, J. O. Simpson, and A. R. Hawthorne, "Modeling and Testing of Formaldehyde Emission Characteristics of Pressed-Wood Products," Report no. 18 to CPSC, Oak Ridge National Laboratory Report no. TM 9867, 1985.

[3] R. A. Grot, S. Silberstein, and K. Ishiguro, "Validation of Models for Predicting Formaldehyde Concentrations in Residences due to Pressed Wood Products -- Phase I," National Bureau of Standards Interagency Report no. 85-3255, Gaithersburg, MD, 1985.

Table 1. Coefficients for the ORNL model

pressed-wood product	c K	A	C_{bstd} ppb	B K^{-1}	E $\%^{-1}$
particleboard underlayment	9,400	0.37	360	0.025	0.016
hardwood-plywood paneling	6,500	0.66	410	0.053	0.029
medium-density fiberboard	5,000	1.90	900	0.090	0.000

Table 2. Mdf loading vs. $ser_{23,50,100}$ in the presence of particleboard and plywood

particleboard $ser_{23,50,100}$	0.736 $mg/m^2 \cdot h$
plywood $ser_{23,50,100}$	0.132 $mg/m^2 \cdot h$
particleboard loading	0.427 m^2/m^3
plywood loading	0.951 m^2/m^3
home HCHO concentration	400 ppb
chamber test temperature	25°C
relative humidity	50%
air exchange rate	0.5 h^{-1}

mdf loading m^2/m^3	mdf $ser_{23,50,100}$ at chamber test concentration of 200 ppb	300 ppb	400 ppb
0.05	2.061	3.448	5.479
0.10	1.031	1.724	2.739
0.15	0.687	1.149	1.826
0.20	0.515	0.862	1.370
0.25	0.412	0.690	1.096
0.30	0.344	0.575	0.913
0.35	0.294	0.493	0.783
0.40	0.258	0.431	0.685
0.45	0.229	0.383	0.609
0.50	0.206	0.345	0.548
0.55	0.187	0.313	0.498
0.60	0.172	0.287	0.457
0.65	0.159	0.265	0.421
0.70	0.147	0.246	0.391
0.75	0.137	0.230	0.365
0.80	0.129	0.216	0.342
0.85	0.121	0.203	0.322
0.90	0.115	0.192	0.304
0.95	0.108	0.181	0.288
1.00	0.103	0.172	0.274

Table 3. Temperature vs. mdf chamber test concentration

relative humidity	50%
air exchange rate	0.5 h^{-1}
mdf $ser_{23,50,100}$	1.724 $mg/m^2 \cdot h$
mdf loading	0.1 m^2/m^3

temperature °C	mdf chamber concentration ppb
22.5	220
23.0	230
23.5	250
24.0	260
24.5	280
25.0	300
25.5	310
26.0	330
26.5	350

Table 4. Relative humidity vs. mdf chamber test concentration

chamber test temperature	25°C
air exchange rate	0.5 h^{-1}
mdf $ser_{23,50,100}$	1.724 $mg/m^2 \cdot h$
mdf loading	0.1 m^2/m^3

relative humidity %	mdf chamber concentration ppb
35.0	150
40.0	190
45.0	240
50.0	300
55.0	350
60.0	420
65.0	490

Table 5. Air exchange rate vs. mdf chamber test concentration

chamber test temperature	25°C
relative humidity	50%
mdf $ser_{23,50,100}$	1.724 $mg/m^2 \cdot h$
mdf loading	0.1 m^2/m^3

air exchange rate h^{-1}	mdf chamber concentration ppb
0.30	410
0.35	370
0.40	340
0.45	320
0.50	300
0.55	280
0.60	260
0.65	240
0.70	230

Table 6. Combined effect on mdf chamber concentration of temperature, relative humidity and air exchange rate

mdf $ser_{23,50,100}$	1.724 $mg/m^2 \cdot h$
mdf loading	0.1 m^2/m^3

temp °C	RH %	air exchange rate h^{-1}	mdf chamber conc. ppb
24.0	40	0.60	150
24.5	45	0.55	210
25.0	50	0.50	300

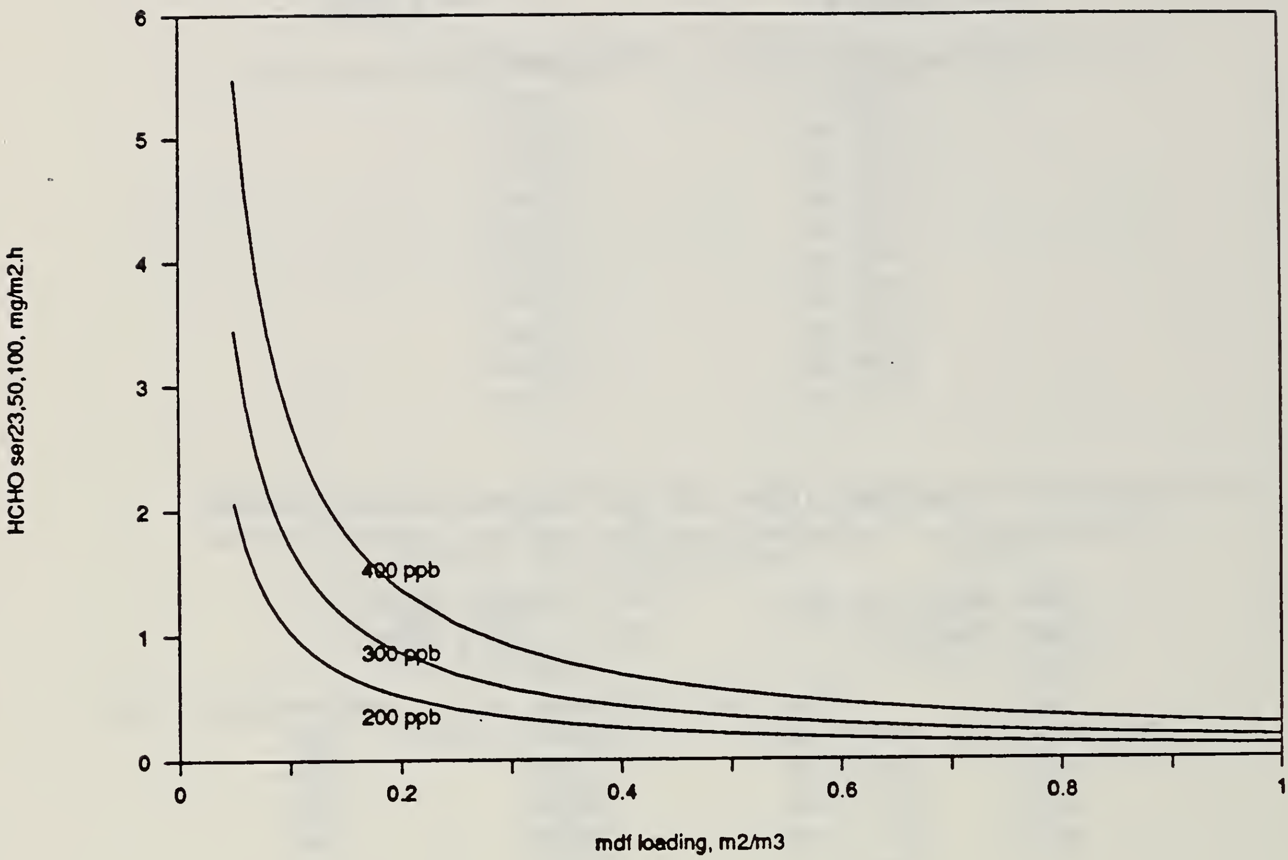

Figure 1. Isoconcentration curves (200, 300, and 400 ppb) showing the combinations of mdf loading and $ser_{23,50,100}$ required to obtain the indicated chamber-test concentrations in the absence of any other formaldehyde emitters. The same combination of mdf loading and $ser_{23,50,100}$ would presumably result in the indicated concentration in a manufactured home in the absence of other emitters. The temperature is 25°C, the relative humidity is 50%, and the air exchange rate is 0.5 h^{-1}. Points on the curve marked "300 ppb" would result in a total concentration of 400 ppb, either in chambers or manufactured homes, in the presence of the maximum loadings of particleboard and plywood permitted by the HUD standards. Particleboard and plywood are assumed to emit formaldehyde at the maximum rate permitted by the HUD standards.

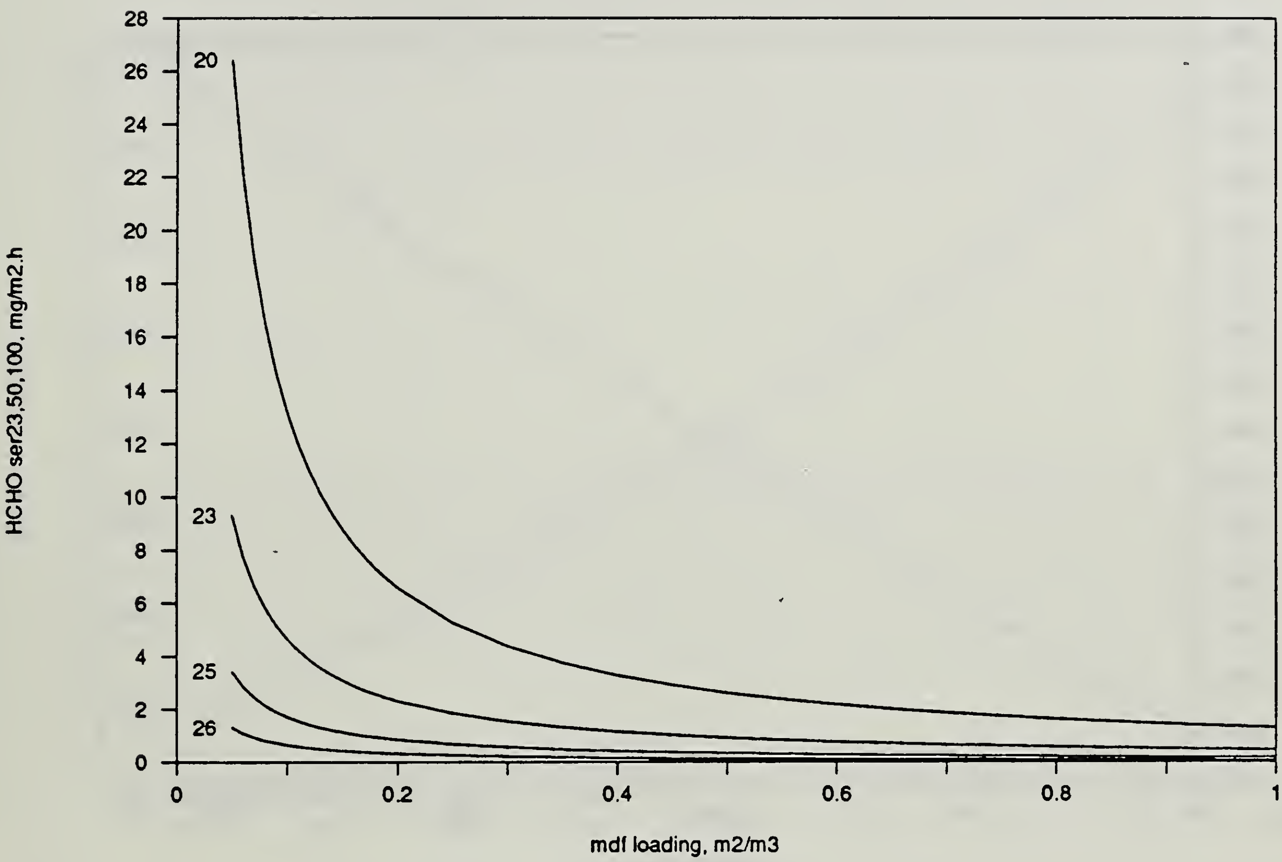

Figure 2. Isoconcentration curves showing combinations of mdf loading and $ser_{23,50,100}$ required to obtain a concentration of 400 ppb at the indicated temperatures (in °C). The relative humidity is 50%, and the air exchange rate is 0.5 h^{-1}. Particleboard and plywood are assumed to be present at the maximum loadings, and to emit formaldehyde at the maximum rates, permitted by the HUD standards.

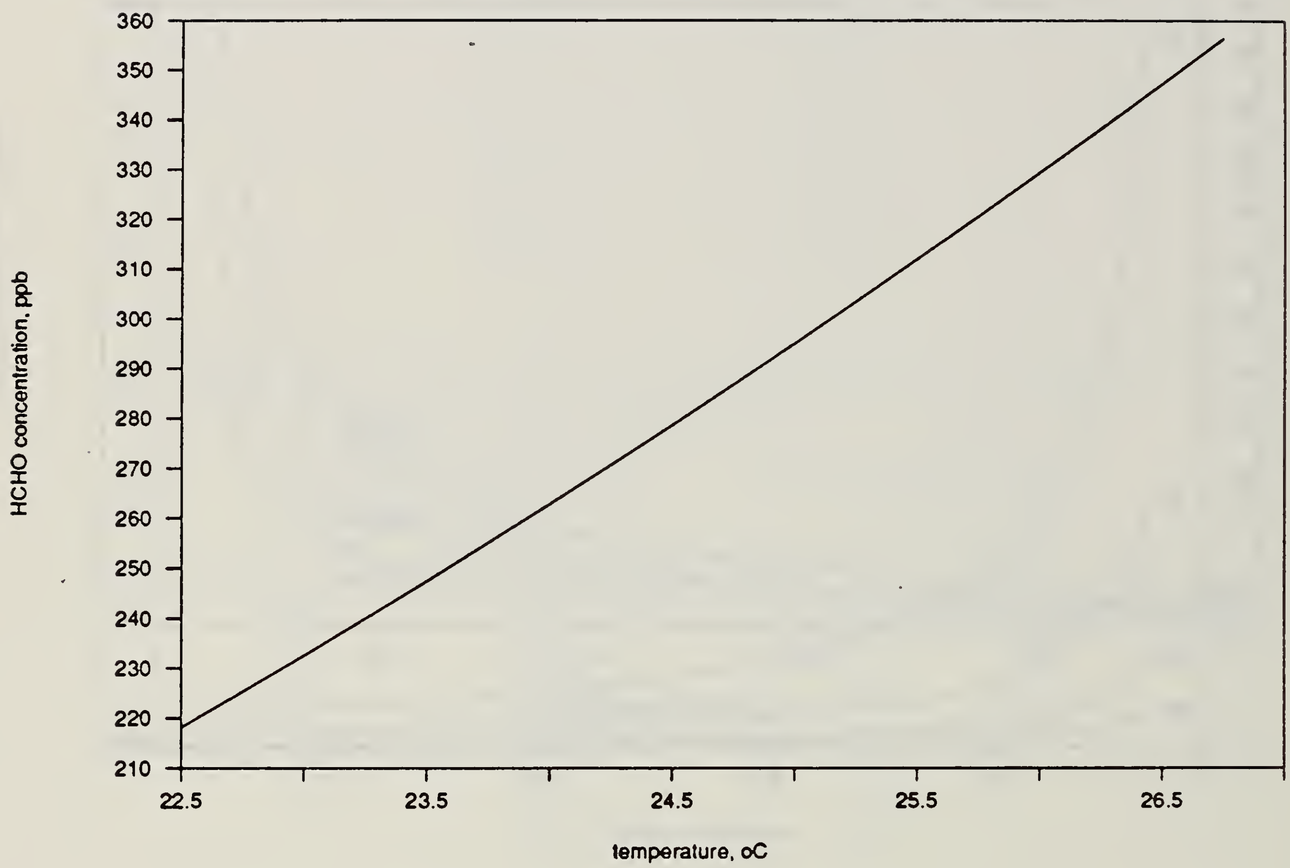

Figure 3. Sensitivity of chamber-test formaldehyde concentrations resulting from mdf to temperature. The relative humidity is 50%, the air exchange rate is 0.5 h^{-1}, and the mdf loading is 0.1 m^2/m^3.

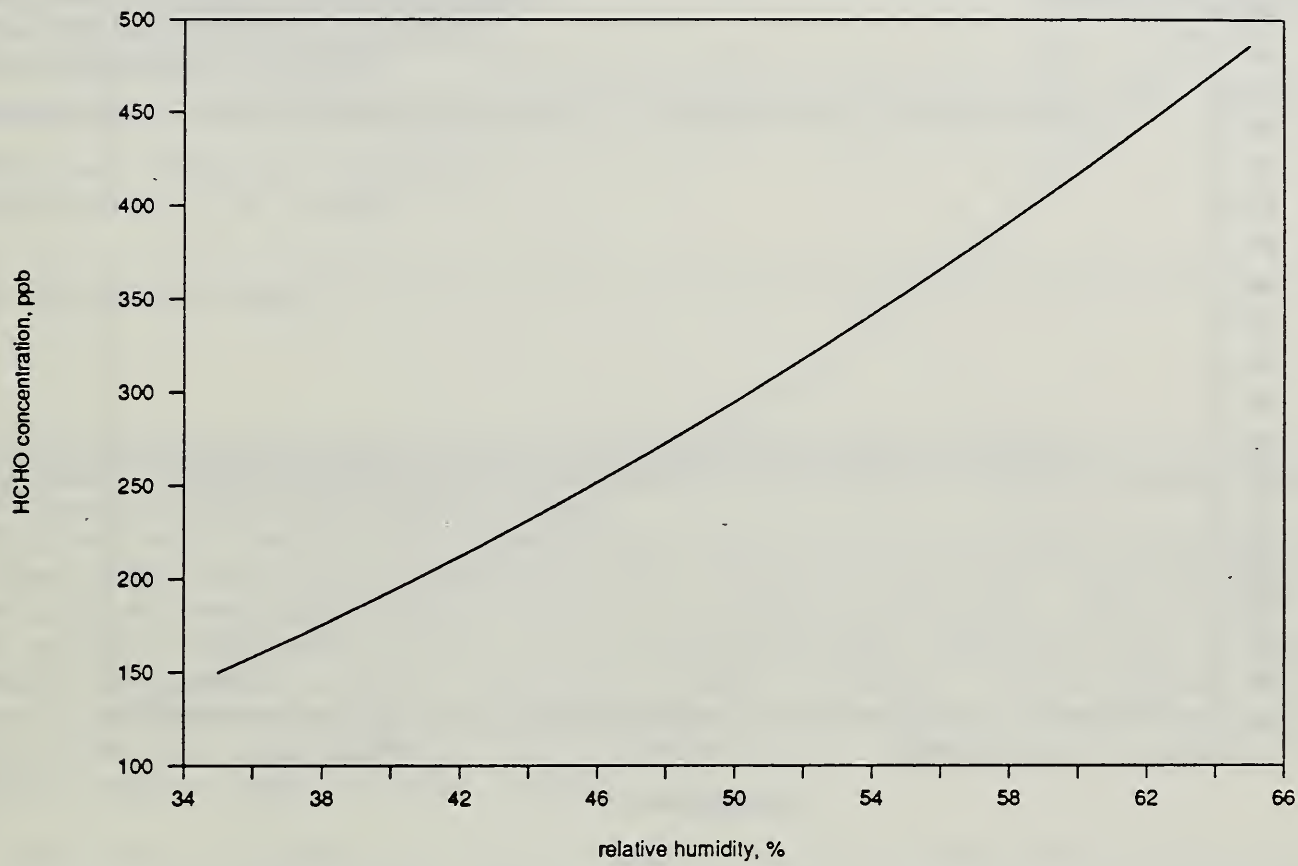

Figure 4. Sensitivity of chamber-test formaldehyde concentrations resulting from mdf to relative humidity. The temperature is 25°C, the air exchange rate is 0.5 h^{-1}, and the mdf loading is 0.1 m^2/m^3.

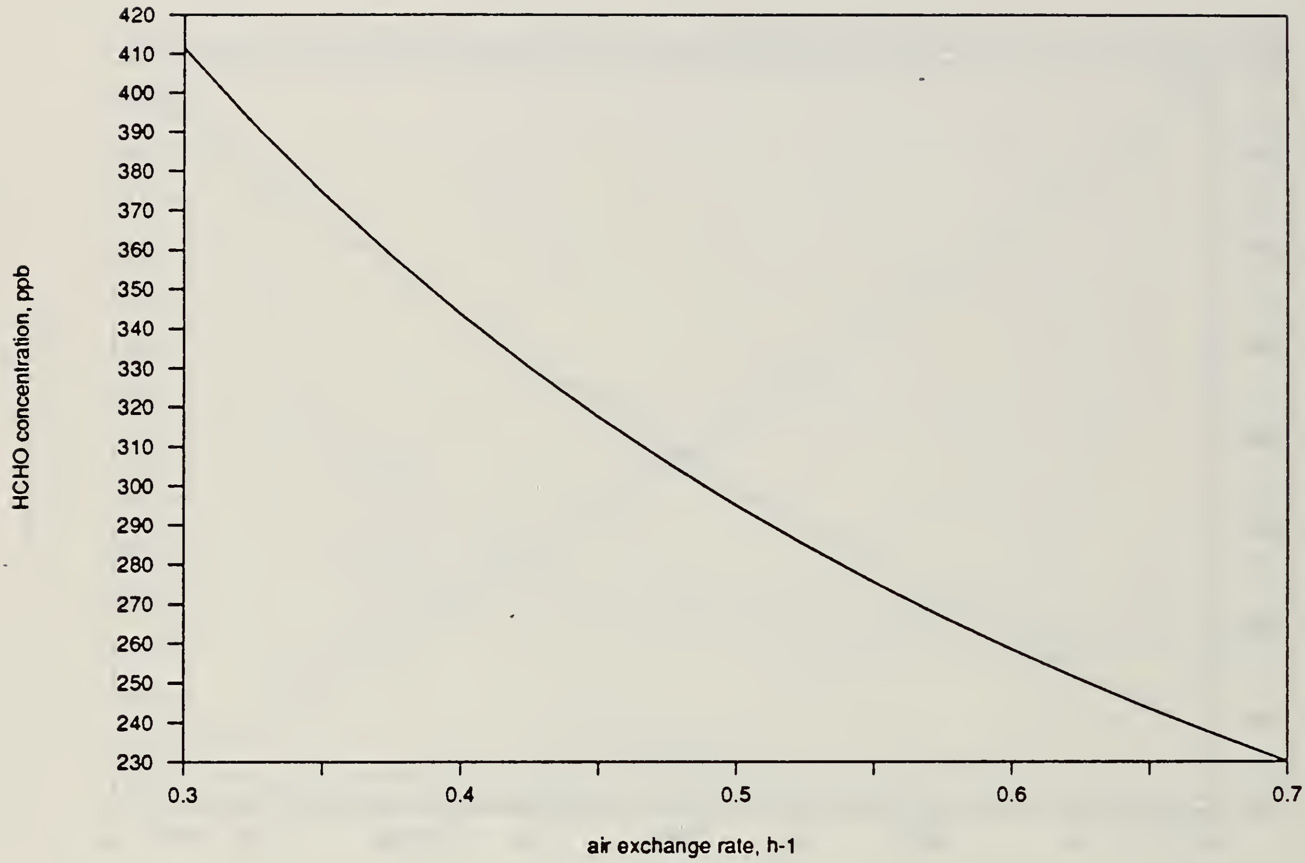

Figure 5. Sensitivity of chamber-test formaldehyde concentrations resulting from mdf concentrations to air exchange rate. The temperature is 25°C, and the relative humidity is 50%, and the mdf loading is 0.1 m^2/m^3.

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 88-3761	2. Performing Organ. Report No.	3. Publication Date MAY 1988

4. TITLE AND SUBTITLE

Predicting Formaldehyde Concentrations in Manufactured Housing Resulting From Medium-Density Fiberboard

5. AUTHOR(S)

Samuel Silberstein

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
U.S. DEPARTMENT OF COMMERCE
GAITHERSBURG, MD 20899

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

National Bureau of Standards
Gaithersburg, MD 20899

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

HUD previously issued Manufactured Home Construction and Safety Standards limiting formaldehyde emissions of particleboard and plywood paneling that were manufactured using urea-formaldehyde resins for use in manufactured homes. This report uses indoor air quality models to predict how much medium-density fiberboard may be added to manufactured homes already containing maximum loadings of particleboard and plywood paneling, without raising the formaldehyde concentration beyond 400 ppb. It was found that any combination of mdf that results in a chamber-test concentration of 300 ppb may be added to such a home.

A sensitivity analysis was done to predict how this formaldehyde concentration limit is affected by variations in temperature, relative humidity, and air exchange rate. It was concluded that limiting chamber concentrations to 200 ppb would allow for small errors in temperature, relative humidity, and air exchange rate that might be expected to arise in practice.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

formaldehyde, medium-density fiberboard, manufactured homes, indoor air quality, modeling.

13. AVAILABILITY

[X] Unlimited
☐ For Official Distribution. Do Not Release to NTIS
☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
[X] Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

18

15. Price

$9.95

USCOMM-DC 6043-P80